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Dynamical evolution of the Hungaria asteroids

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ABSTRACT

The Hungarias are a stable asteroid group orbiting between Mars and the main asteroid belt, with high inclinations (16–30°), low eccentricities ($e < 0.18$), and a narrow range of semi-major axes (1.78–2.06 AU). In order to explore the significance of thermally-induced Yarkovsky drift on the population, we conducted three orbital simulations of a 1000-particle grid in Hungaria a–e–i space. The three simulations included asteroid radii of 0.2, 1.0, and 5.0 km, respectively, with run times of 200 Myr. The results show that mean motion resonances—martian ones in particular—play a significant role in the destabilization of asteroids in the region. We conclude that either the initial Hungaria population was enormous, or, more likely, Hungarias must be replenished through collisional or dynamical means. To test the latter possibility, we conducted three more simulations of the same radii, this time in nearby Mars-crossing space. We find that certain Mars crossers can be trapped in martian resonances, and by a combination of chaotic diffusion and the Yarkovsky effect, can be stabilized by them. Therefore, some Hungarias (around 5% of non-family members with absolute magnitudes $H < 15.5$ and 10% for $H < 17$) may represent previously transient Mars crossers that have been adopted in this manner.

1. Introduction

The Hungarias are a distinct population of asteroids located in a swath between 1.78 and 2.06 AU. Bounded by the ν_5 and ν_{16} secular resonances,[1] the 4:1 mean motion resonance with Jupiter, and Mars-crossing orbital space (Gradie et al., 1979; Milani et al., 2010), its members have relatively high inclinations ($16° < i < 34°$) and eccentricities typically less than 0.18. The Hungarias make up the closest distinct region of the asteroid belt to the Sun, lying interior to the inner main belt by at least 0.1 AU. The region derives its name from its largest and earliest known member, (434) Hungaria. This asteroid has also been identified as the largest fragment of what is likely to be the region's sole asteroid family, created by a catastrophic collision about 0.5 Gyr ago (Warner et al., 2009). A majority of the approximately 5000 bodies in the region are thought to be part of this family. Almost all known Hungarias are brighter than absolute magnitude $H = 18$, meaning they are about 1 km in diameter or larger.

A noteworthy feature of the Hungaria group is their range of taxonomic classes. E and X spectral types are the most common, followed by S types, Cs, and As (Warner et al., 2009). All these bodies are found in the main belt with different spatial distributions and prevalence. The abundance of E types among the Hungarias is fascinating because E types are very rare in other asteroid populations. Clark et al. (2004) listed only 10 known E-type asteroids outside the Hungaria region. E-type asteroids have extremely high albedos (>0.34, with the majority >0.4; Tedesco et al., 1989; Gaffey and Kelley, 2004) and exhibit a range of curious spectra. Many spectra are consistent with aubrite meteorites[2] suggesting they might be the mantle material of parent bodies that differentiated in highly reducing conditions (Gaffey and Kelley, 2004). Based on their current distribution, it is most likely that they originated from the terrestrial planet zone, interior to most other asteroid types.

2. Preliminary experiment

Before examining long-term evolution of various-sized bodies in the Hungaria region, we decided to use a simple integration to test if the largest Hungarias could have been stable over the age of the Solar System, when taking into account the Yarkovsky effect.[3] In a preliminary experiment, we integrated the orbits of some 30 large asteroids in the Hungaria region (which turned out to in-

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[1] The ν_5 is the secular resonance at which the apsidal motion of an asteroid (i.e. the precession of its pericenter) is equal to the fifth secular apsidal frequency. Across the asteroid belt this occurs at a proper inclination around 30°. The ν_{16} is the secular resonance at which the nodal motion of an asteroid (i.e. the precession of its node) is equal to the sixth secular nodal frequency. This resonance lives near 2.0 AU.

[2] Aubrites are differentiated stony meteorites consisting primarily of enstatite with very low Fe content. Also known as enstatite achondrites.

[3] The Yarkovsky effect is a perturbation of an asteroid's orbit resulting from the recoil from its thermal radiation. The integrated momentum carried by thermal photons is offset from the Sun–asteroid line due to thermal inertia, resulting in a along-orbit force modifying the semi-major axis (see Bottke et al. (2006a,b) for a recent review).

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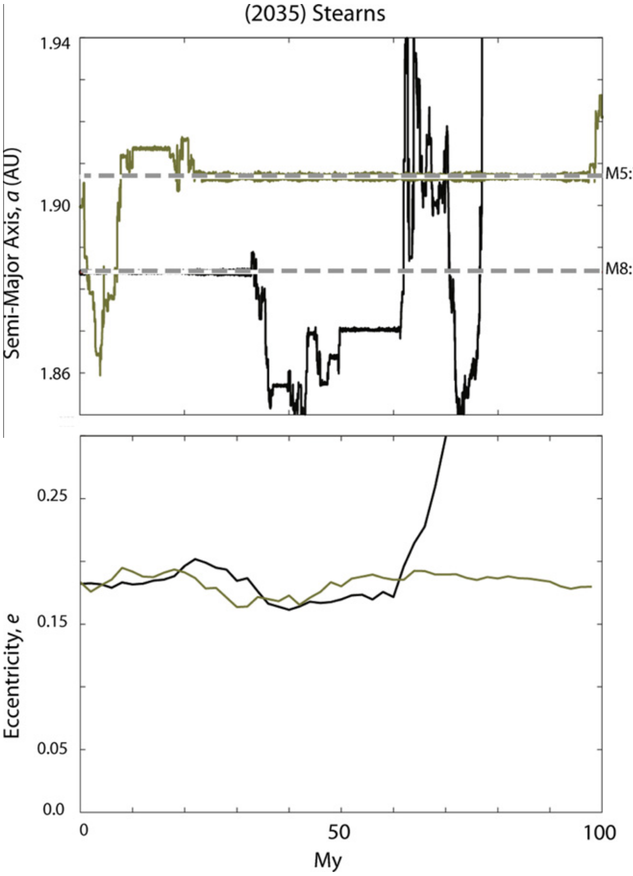

Fig. 1. Martian resonances catch Mars crossers for long durations. Osculating semi-major axis (top panel) and averaged eccentricity (bottom panel) of Asteroid (2035) Stearns over 100 Myr. Black plot is with today's initial conditions. Gray plot is with same initial conditions but with a shift in semi-major axis. Both get stuck to martian resonances for tens of millions of years. Eccentricities are plotted as running averages over a 5 Myr box.

clude some transient Mars crossers) from present initial conditions to 100 Myr in the future, using Rauch and Hamilton's symplectic integrator, HNBody (Rauch and Hamilton, 2002). These 30 large asteroids all had taxonomic classes listed on the JPL small-body database following the conventional Tholen classification (Tholen, 1984). We also conducted four nearly identical simulations, but with the 30 orbits shifted in semi-major axis. The shift was based on expected Yarkovsky drift over 0.5 and 1.0 Gyr, using parameters taken from Bottke et al. (2006b). All eight planets were included into the integration and the timestep was 1 day. Our primary aim was to study the future dynamical behavior of these asteroids and to characterize the region's general limits of stability. Some of our asteroids were incidentally shifted onto martian resonances, which proved to have significant dynamical effects.

Fig. 1 demonstrates how Mars crossers can stick to martian resonances (here "Mars crossers" means objects exhibiting kicks in the semi-major axis caused by close approaches to Mars). The Mars crosser (2035) Stearns stays in the martian 8:11 resonance for over 30 Myr during the nominal, unshifted simulation (black plot). This is because an asteroid is protected from encountering the planet it is in resonance with, even if the asteroid's eccentricity is high (Murray and Dermott, 1999). When shifted, Stearns randomly walks in semi-major axis through martian encounters (gray plot,) until it gets stuck to the 5:7 resonance, staying for as long as 70 Myr. Because of (2035) Stearns' chaotic nature, these simulations are not to be taken as definitive predictors of behavior, but nevertheless show how Mars crossers, although unstable, can remain in the Hungaria region for long periods due to resonance sticking.

Asteroids can chaotically jump from being near a resonance to being in a resonance and vice versa. In Fig. 2, a shifted orbit of (1355) Magoeba (gray plot) begins near, but not in, the 3:4 resonance. This situation continues for the first half of the simulation, but by 50 Myr Magoeba librates around 1.8458 AU, indicating that it has become resonant. The resonance also causes Magoeba's variations in semi-major axis and eccentricity to be more pronounced, the latter staying above the average eccentricity of the nominal unshifted simulation (black plot) for nearly the entire 100 Myr. Like Magoeba, (1727) Mette's eccentricity is greatly affected by the 3:4 resonance; its value dips significantly above and below the nominal eccentricity of the non-resonant simulation.

This preliminary numerical experiment was purely gravitational, and having shown that the local resonances could noticeably impact the Hungarias, it was necessary to do more comprehensive simulations: particularly, ones that incorporated the Yarkovsky effect. The Yarkovsky effect is especially important for the dynamical evolution of the Hungarias for several reasons. Firstly, because Yarkovsky is insolation-driven, the orbital migration among the Hungarias than in the more distant main belt (this might be partially offset by higher albedos in the case of numerous E-type Hungarias). Secondly, the region's small size allows asteroids to drift across significant fractions of its 0.2 AU width, not only leading them into resonances, but in some cases out of the stable region entirely. The combination of Yarkovsky drift and resonances is known to deplete asteroids from the main belt (Bottke et al., 2006b), and the same process has likely lead to the loss of many Hungarias. Finally, the Yarkovsky effect may play a role in population exchange between Mars crossers and Hungarias, which we will explore later in this paper.

3. Experiment 1: Hungaria grid

We conducted three simulations of 1000 test asteroids starting in stable Hungaria space ($1.8 < a < 1.98$ AU, $16^\circ < i < 25^\circ$, and perihelia outside 1.66 AU). The simulations tested asteroid radii of 0.2, 1.0, and 5.0 km (with randomized obliquities), and were run for 200 Myr. We used the symplectic integrator SWIFT-rmvs3y by Miroslav Brož to evolve the orbits (Brož, 2006). Brož's package is a modification of a widely used integrator, SWIFT (by Duncan et al. (1998)) in a number of ways, most notably in including Yarkovsky drift.

Our simulations are significantly longer than the natural eigenperiods of the Solar System. Therefore, if a body remains stable over the course of the simulation, it is likely (except in cases of very slow chaotic diffusion) that its orbit is indeed stable against gravitational perturbations. For example, Tabachnik and Evans (2000) used 100-Myr simulation to sufficiently characterize the stability of inner Solar System asteroid repositories. Yarkovsky effect can cause instability on longer timescales (by slowly drifting asteroids into resonances), so in principle running longer simulations would be useful if computationally expensive. However, we expect even 5-km bodies to significantly change their rotational state over 200 Myr, making Yarkovsky evolution on longer timescales somewhat of a stochastic process. While the SWIFT-rmvs3y is fully cabale of taking YORP reorientation into account, we decided to simply extrapolate our results to longer timescales assuming our 200-Myr simulations are typical of the long-term history of the bodies in question. The last assumption may not be correct for some of our largest bodies, as discussed below.

We used a timestep of three days, outputting orbital elements of each body every 100,000 years. The simulations in this paper